800-Gbps PAM-4 O-band Transmission through 2-km SMF using 4λ LAN-WDM TOSA with MLSE Based on Nonlinear Channel Estimation and Decision Feedback

Hiroki Taniguchi(1), Shuto Yamamoto(1), Yoshiaki Kisaka(1), Shigeru Kanazawa(2)

, Toshihide Yoshimatsu(2), Yozo Isikawa(3), Kazuyo Mizuno(3)

(1) NTT Network Innovation Laboratories, NTT Corporation, hiroki.taniguchi.ys@hco.ntt.co.jp
(2) NTT Device Innovation Center, NTT Corporation
(3) Furukawa Electric Co. Ltd.

Abstract *We demonstrate 224-Gbps/λ 2-km transmission using 4-ch LAN-WDM TOSA with integrated SOAs and EADFB lasers. We achieve a BER below the HD-FEC limit for all channels in the 10-dB bandwidth of 34.8-GHz and chromatic dispersion of –4.2-ps/nm with advanced nonlinear MLSE based on decision feedback.*

Introduction

With the growing use of cloud services in recent years, increasing network traffic within and between data centres (DCs) is a major challenge. At present, Ethernet is the mainly used connection within and between DCs. Currently, 400GbE is standardized in IEEE802.3 and 800GbE/1.6TbE have been set as future milestones. The capacity of Ethernet has become high due to an increase in the modulation speed, symbol level, and number of wavelength channels in intensity modulation schemes and direct detection (IM-DD) systems, and it can now achieve economical short-reach transmission. For 400GbE, 50-Gbps or 100-Gbps PAM-4 (4-level pulse-amplitude-modulation) and wavelength division multiplexing (WDM) are utilized in the O-band. To achieve 800GbE/1.6TbE, 200-Gbps per channel PAM-4 is required. This increase in modulation speed and the number of wavelength channels will lead to bandwidth limitation due to transmission systems using narrowband and low-cost devices and chromatic dispersion (CD) due to the increased number of wavelength channels. The inter signal interference (ISI) caused by these factors distorts the waveform of the received signal. Several studies have addressed these problems of IM-DD systems with high baud rate signal transmission[1]–[3]. Maximum likelihood sequence estimation (MLSE) has also been studied as a receiver-side digital signal processing technique for powerful channel equalization methods[4],[5]. We previously investigated advanced MLSE to obtain the correct transmission data from received signal waveforms non-linearly distorted by ISI[6],[7]. However, when it comes to the performance of this method, which we call nonlinear MLSE (NL-MLSE), the problem is that the computational complexity increases with the length of the series to be estimated.

In this paper, we propose NL-MLSE with decision feedback (DF-NL-MLSE) to improve the estimation accuracy while reducing the computational complexity. We also demonstrate 800-Gbps, PAM-4, and 2-km transmission using 4-ch LAN-WDM TOSA and DF-NL-MLSE.

NL-MLSE with Decision Feedback

Figure 1 shows a block diagram of the proposed DF-NL-MLSE. This method consists of three adaptive filters, a Viterbi decoder, and a candidate sequence generator. The first filter is a channel shortening filter (CSF) that fixes the sampling phase of the received signal and shortens the overall impulse response length of received signal sequences to suppress the increase in calculation amount in accordance with the memory length of the Viterbi decoder. The second filter is an adaptive low pass filter (A-LPF) that suppresses high-frequency noise components that were increased by the CSF in the previous stage. The third filter is a desired impulse response (DIR) filter that converges with the same distance function as the A-LPF, so that it can simulate the frequency response of the transmission line, i.e., the frequency response that is least affected by Gaussian noise.

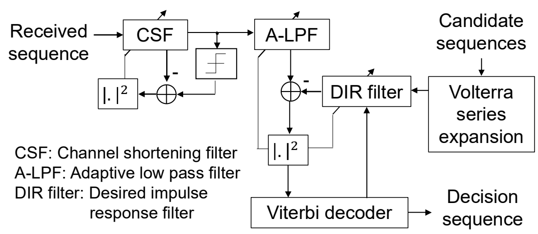

Fig. 1: Block diagram of DF-NL-MLSE.

Generally, the inputs of the DIR filter are generated by the Viterbi algorithm as candidate sequences. In NL-MLSE, the transmission line response including nonlinear ISI is estimated by implementing a Volterra series expansion on the candidate series. If the length of a candidate sequence is five symbols, the MLSE obtains 4^5 = 1024 candidate sequences and calculates the DIR filter output 1024 times for each symbol decision. To improve the performance of the MLSE, it is necessary to increase the length of the candidate series so that we can increase the accuracy of the likelihood calculation used by the Viterbi-decoder, but the length of this series exponentially increases the amount of computation.

Therefore, our proposed method feeds back some of the decision results of the Viterbi decoder to the input of the DIR filter to increase the length of the input series to the DIR filter without changing the number of candidate series and to improve the accuracy of the calculated likelihood. For example, if the length of the candidate series is three symbols and the decision feedback is two symbols, the output of the nonlinear DIR filter can be expressed as

$$f(\hat{d}_{-4},\hat{d}_{-3},c_{-2},c_{-1},c_0)=\sum_{a=-4}^{-3}p_a\hat{d}_a + \sum_{a=-2}^{0}q_a c_a + \sum_{a=-2}^{0}\sum_{b=-2}^{0}r_{ab}c_a c_b + \sum_{a=-2}^{0}\sum_{b=-2}^{0}\sum_{c=-2}^{0}s_{abc}c_a c_b c_c \qquad (1),$$

where $(\hat{d}_{-4},\hat{d}_{-3})$ is a decision feedback series from the Viterbi decoder, (c_{-2},c_{-1},c_0) is a candidate series, and ($p_{-4,-3}$, $q_{-2\sim0}$, $r_{-2-2\sim00}$, $s_{-2-2-2\sim000}$) are taps and kernels of the DIR filter. In this case, the number of candidate sequences is only 4^3 = 64 and by applying the decision feedback, the number of DIR filter output calculations can be reduced by a factor of 16 when a series of the same length (five) is put into the DIR filter.

Experiments and Results

We experimentally evaluate the performance of the proposed DF-NL-MLSE in 4-ch high-baud-rate PAM-4 transmission. Figure 2 shows the experimental setup. Transmission data sequences of 224-Gbps PAM-4 signals are generated by off-line DSP and a 65-GHz, 112-Gsample/s arbitrary waveform generator (AWG). In this experiment, a 15th-order pseudo-random binary sequence is utilized. The electrical PAM-4 signals are modulated to 4-ch WDM optical signals by a 4-λ LAN-WDM TOSA that consists of electro absorption modulated lasers (EMLs) with integrated semiconductor optical amplifiers (SOAs) and a wavelength multiplexer [8]. The optical signals are transmitted to 2-km SMF without any optical amplifiers. Transmitted optical signals are received with a 50-GHz PIN photodiode (PD) after implementing a wavelength de-multiplexer (LAN-WDM DeMUX) and a variable optical attenuator (VOA). The amount of chromatic dispersion is −4.2 ps/nm in the case of 2-km transmission at 1295 nm. The received signals are then converted into a digital signal sequence by a 65-GHz, 160-Gsample/s digital storage oscilloscope (DSO) and demodulated by the FFE and the MLSE with or without decision feedback. The FIR filter in the FFE and the CSF in the MLSE have 45 T/2-spaced taps. The numbers of taps for the A-LPF and the DIR filter are set to the sum of candidate sequence length and the number of decision feedback symbols. They have T-spaced taps. The FIR filter, the CSF, the A-LPF, and the DIR filter are updated by the recursive least squares algorithm. To ensure the correct adaptation of the filters, the taps in the filters are trained beforehand by the first 1000 symbols. Figure 3 shows the frequency responses of the transmission system, where we can see that the 10-dB frequency bandwidth is 34.8 GHz.

Figure 4 shows the results of 112-GBd PAM-4 in 2-km transmission for all lanes where the received optical power is 2 dBm. These results show that demodulation by the FFE (triangle) and conventional MLSE (circle), cannot achieve a BER below 3.8×10^{-3}, which corresponds to the 7% overhead HD-FEC limit in all wavelength channels.

Moreover, applying NL-MLSE (square) and conventional MLSE with decision feedback (DF-MLSE) (asterisk) cannot achieve the HD-FEC limit in some wavelength channels.

In contrast, the application of DF-NL-MLSE

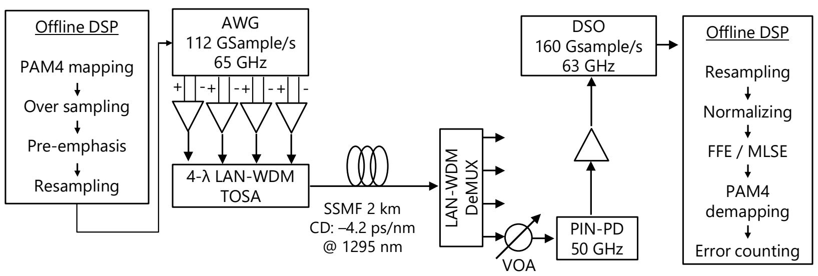

Fig. 2: Experimental setup of 4-ch LAN-WDM transmission system.

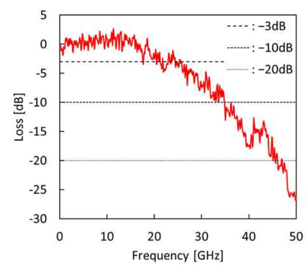

Fig. 3: Frequency responses of the transmission system.

(diamond) achieved below the HD-FEC limit in all wavelength channels.

Figure 5 shows the relationships between the received optical power and BER at lane 0 (1295 nm) in 2-km transmission for FFE (triangle), MLSE (square, dashed line), NL-MLSE (circle, dashed line), DF-MLSE (square, solid line) and DF-NL-MLSE (circle, solid line). We ca see here that the addition of decision feedback to MLSE significantly improves the performance and the receive sensitivity is improved 0.8 dB at the HD-FEC limit by applying Volterra series expansion in MLSE with decision feedback.

Figure 6 shows a comparison of the performance of the DIR filter for different input sequence lengths. Even though this length is increased by decision feedback, the performance is degraded when the length is greater than five. This is because the convergence of the tap coefficients becomes more difficult as the number of taps in the decision feedback increases.

In Figure 7, s_{abc} represents the absolute values of the third-order kernels when the candidate series length is five symbols in the aforementioned equation (1) without decision feedback. We can see that the dark-coloured kernels with large values are gathered near the three symbols including the main symbol (number 0). Therefore, the nonlinear component for three symbols is calculated from the candidate series including the linear component, and the linear component for two additional symbols is calculated from the decision feedback, which efficiently reduces the amount of MLSE calculation.

Conclusions

We proposed DF-NL-MLSE to improve the transmission performance with less computational complexity. Experimental results showed it could achieve a BER below the 7% HD-FEC threshold for 800-Gb/s PAM-4 signal, 2-km O-band transmission in the 10-dB bandwidth of 34.8-GHz.

We also demonstrated a significant improvement by applying Volterra series expansion and decision feedback to the input sequence of the DIR filter in MLSE.

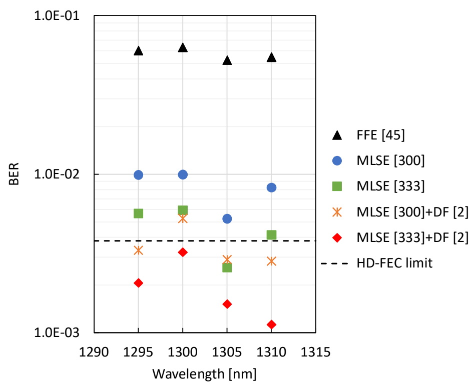

Fig. 4: 224-Gbps/λ PAM-4 performance in 2-km transmission.
(FFE: triangle, conventional MLSE: circle, NL-MLSE: square, conventional MLSE with DF: asterisk, DF-NL-MLSE: diamond)

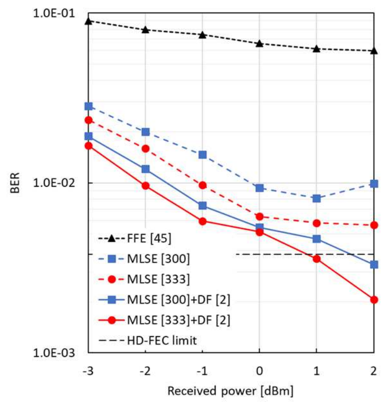

Fig. 5: 224-Gbps/λ PAM-4 performance comparison in 2-km transmission at lane 0. (FFE: triangle, conventional MLSE: square, NL-MLSE: circle, without DF: dashed line, with DF: solid line)

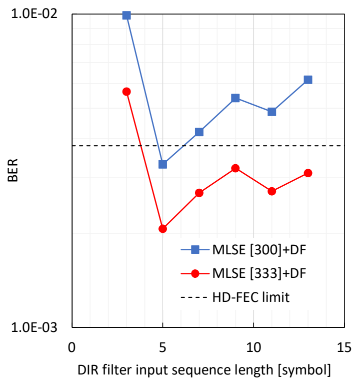

Fig. 6: Performance comparison for different input sequence lengths of DIR filter. (Conventional MLSE: square, NL-MLSE: circle)

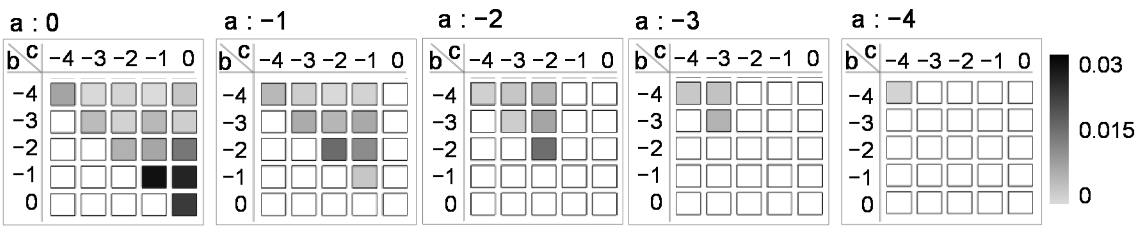

Fig. 7: Absolute kernel values of 3rd order components s_{abc} after convergence.

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